Milestone Report

Fuel Cell Integration–A Study of the Impacts of Gas Quality and Impurities

Milestone Completion Report

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For the Chemistry of BioEnergy Systems Division of the National BioEnergy Center

NREL

National Renewable Energy Laboratory

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EXECUTIVE SUMMARY

This report is a review of the recent literature exploring the issues of integrating fuel cells with various sources of fuel gas, with particular attention to the fuel-processing step of a fuel cell system. A brief discussion of the available fuel cell technologies is presented highlighting the tolerances of fuel cell systems to impurities in the fuel gases. For a more comprehensive description of fuel cell systems, please consult the Fuel Cell Handbook (5th edition, 2000). This report also outlines a description of several sources of fuels and their compositions followed by a discussion how these fuel sources might be integrated with fuel cell systems for distributed and centralized power production.

Ancillary components in a fuel cell power plant account for only half of the size of a fuel cell system yet account for nearly all of the unscheduled outages in hydrocarbon-fueled fuel cell systems. Components that require considerable attention are the fuel processing system, acid gas removal systems, and halogen guard beds.

Acid gas removal systems will be required in all hydrocarbon reforming fuel cell systems because both fuel cells and steam reforming catalysts do not tolerate sulfur. They will be necessary even for natural gas, the simplest hydrocarbon fuel. Halogen guard beds will likely be required for all fuel cell power systems as well to minimize long term, high temperature corrosion.

Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) operate at high temperatures and therefore offer the best opportunity for thermal integration with coal and biomass gasification systems. The technical challenge will be to design a fuel processing system to pre-condition the product gases before they enter the fuel cell stack. Particulate removal will be required in integrated gasification fuel cell systems to remove carried over bed material and ash. Removal of biomass and coal ash is needed to control alkali metal contamination. Hot gas filtration or quenching is an option for removing high temperature alkali metal vapors from biomass and coal. Tar removal will also be necessary to avoid plugging fuel lines, fouling catalytic sulfur removal systems, and prevent coke formation on the fuel cell electrodes and steam reforming catalysts.

The incredibly variable coal and biomass feedstock compositions pose a significant challenge for integrated gasification fuel cell systems. This would suggest that fuel-processing systems will have to be customized for many individual situations. Customization will require integrating the sub-systems in a fuel processor and poses significant engineering and technical challenges in the design and integration of gasification systems, fuel processing systems, and fuel cell stacks.

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ACRONYMS AND ABBREVIATIONS

$(NH_4)H_2PO_4$ – ammonium phosphate salt
AFC – Alkaline Fuel Cells
atm - atmosphere
Au – gold
$BaCO_3$ – barium carbonate
$CaCO_3$ – calcium carbonate
CH_4 – methane
CO – carbon monoxide
CO_2 – carbon dioxide
CO_2^{2-} – carbonate anion
COS – carbonyl sulfide
Cr -chromium
CuO – copper oxide
FeO – iron oxide
H_2 – hydrogen
H_2S – hydrogen sulfide
H_3PO_4 – phosphoric acid
HC – hydrocarbon
HCN – hydrogen cyanide
HHV – higher heating value
IEMFC – Ion Exchange Membrane Fuel Cells
K – potassium
K_2CO_3 – potassium carbonate
KOH – potassium hydroxide
kW – killowatt
$LaMnO_3$ – lanthanum manganate
Li – lithium
$LiAlO_2$ – lithium aluminate
mA/cm^2 – current density

MCFC – Molten Carbonate Fuel Cells
MSW – municipal solid waste
MW – megawatt
N_2 – nitrogen
Na – sodium
NH_3 – ammonia
Ni – nickel
NiO – nickel oxide
NO – nitric oxide
NO_x – nitrogen oxides
O_2 – oxygen
OH^- - hydroxide anion
PAFC – Phosphoric Acid Fuel Cells
Pd – paladium
PEFC – Polymer Electrolyte Fuel Cells
PEMFC – Proton Exchange Membrane Fuel Cells
ppm – parts per million
ppmv – parts per million volume
Pt – platinum
SiC – silicon carbide
SiO_2 – silicon dioxide
SOFC – Solid Oxide Fuel Cells
SO_x – sulfur oxides
$SrCO_3$ – strontium carbonate
V – volt
vol% - volume percent
wt% - weight percent
YSZ – yttrium stabilized zirconia
ZnO – zinc oxide

1   INTRODUCTION

The basic operating principles of fuel cells have been known since the assembly of the first hydrogen fuel cell in 1839 by William R. Grove [Appleby, 1996]. Over the last half century, a variety of fuel cells have been developed for space exploration, transportation, and stationary power generation. In general, a fuel cell is an electrochemical device that directly converts the chemical energy of a fuel/oxidizer mixture into electricity. The direct conversion of fuel into electricity means that fuel cells operate at higher efficiencies (~50-65% based on the LHV of natural gas) than conventional power generation systems that convert fuel into heat that produces mechanical work for electricity production. Conventional power generation systems are Carnot limited and lose efficiency because of thermodynamic and mechanical limitations in the system. Fuel cell system efficiencies are relatively constant and independent of the size of the system and load. A single fuel cell consists of an anode and a cathode separated by an electrically insulating electrolyte. Individual fuel cells often provide less than 1 V at a current density on the order of 200 mA/cm^2, therefore, fuel cells are stacked to achieve desired electrical power output. Interconnectors separate the individual fuel cells in a stack.

Aside from efficiency considerations, fuel cells offer several other advantages over conventional power systems. In today's climate of increasing environmental awareness, fuel cell systems have the potential to substantially reduce air and water emissions associated with electricity production. In all fuel cell systems, hydrogen is consumed at the anode and water is produced at the cathode. Therefore, in principle, the only by-product of electricity production in a fuel cell is water. The higher system efficiencies for fuel cells translate into enhanced fuel utilization and therefore reduced CO_2 emissions compared to lower efficiency systems. Fuel cell power plants will be capable of exceeding stringent present and future environmental regulations for particulates, NO_x, and SO_x emissions. In addition, the absence of mechanical equipment in fuel cell systems greatly reduces the noise associated with conventional power plants and fuel cell power plants have high reliability with low maintenance.

Without considering batteries and other chemical storage devices, there are effectively six types of primary or direct fuel cell technologies currently being developed: alkaline fuel cells (AFC), polymer electrolyte fuel cells (PEFC), a specialized polymer electrolyte fuel cell using methanol as the fuel called the direct methanol fuel cell, phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC) [Kordesch and Simader, (1996); Cappadonia, et al. (2000); Kinoshita and Cairns, (1994)]. These technologies are at various stages of commercialization [Penner, et al. (1995); Appleby (1996)] and individual fuel cell systems have different applications [Kordesch and Simader, (1996)]. The high cost of fuel cell systems ($1000 –$20,000/kW) is one of the more significant barriers to commercialization [Appleby, (1996)].

One of the first commercial applications of fuel cells involved using AFCs for manned space missions. They were used to power the Apollo space missions and are currently used in the Space Shuttle. AFCs are at the high end of efficiency for fuel cell systems, however, they require pure H_2 and O_2 as reactant gases and are very sensitive to impurities that shorten operational lifetimes. Because of these issues and the expensive materials of construction required, alkaline fuel cells tend to be very expensive.

An extension of using fuel cells for space missions is the development of ultra-low emission terrestrial vehicles powered by fuel cells. Fuel cells offer an alternative to rechargeable storage batteries that are heavy, have low power densities, and require long recharging times. Fuel cells acting as power generators in vehicles can provide higher power densities from fuels on demand with relatively fast refueling times [Kordesch and Simader; (1996), Fuel Cell Handbook (2000)]. Based on the success of the alkaline fuel cells in spacecraft, these systems were the first fuel cells used in vehicles and have performed well in electric vehicles. The fuel requirements and associated costs have led to the search for alternative fuel cell technologies for vehicle applications. PAFCs and PEFCs are also being investigated for transportation

applications. It is unlikely that the higher temperature MCFCs and SOFCs will be viable for transportation applications.

The other application of fuel cell systems is for distributed and centralized power production. In a changing and restructuring electric utility industry, fuel cells offer the opportunity to provide additional large-scale and distributed capacity with higher energy efficiency and greater environmental performance. PAFC systems are commercially available for distributed and centralized power production [Spiegel, et al. (1999); Spiegel, et al. (2000); Penner, et al. (1995)]. The largest fuel cell power plant in the world is an 11 MW PAFC system operating on reformed natural gas located at the Goi Thermal Power Station in Japan. In fact, the Japanese are aggressively developing PAFC systems for utility power production [Hojo, et al. (1996); Horinouchi, et al. (1998); Kasahara, et al. (2000)].

The need for increased fuel flexibility and greater resistance to impurities was a motivation for developing high temperature MCFC and SOFC systems. These systems are currently in various stages of development and demonstration, although molten carbonate fuel cell systems are nearer to commercialization [Eichenberger, (1998); Figueroa and Otahal, (1998); Steinfeld, et al. (2000)]. Unlike PAFC systems, MCFCs can tolerate the high concentrations of CO that are produced in natural gas reforming and coal or biomass gasification [Huijsmans, et al. (2000); Steinfeld, et al. (2000); Fuel Cell Handbook (2000)]. This eliminates the need for water gas shifting and selective CO oxidation that would otherwise increase system costs and reduce overall efficiency. The higher operating temperatures of MCFC systems also provide an opportunity for co-generation or waste heat utilization that could improve overall system efficiency to ~85% (LHV) [Craig and Mann, (1996); Lobachyov and Richter, (1998); Amos (1998)].

This report is a review of the recent literature exploring the issues of integrating fuel cells with various sources of fuel gas, with particular attention to the fuel-processing step in a fuel cell system. A brief discussion of the available fuel cell technologies will be presented highlighting the tolerances of these systems to impurities in the fuel gases. For a more comprehensive description of fuel cell systems, please consult the Fuel Cell Handbook (5th edition, 2000) and other references [Cappadonia, et al. (2000); Kordesch and Simader, (1996); Kinoshita and Cairns, (1994)]. A description of several sources of fuels and their compositions is also presented followed by a discussion of how these fuel sources might be integrated with fuel cell systems for distributed and centralized power production.

2 TYPES OF FUEL CELL SYSTEMS

Fuel cells are classified according to the type of electrolyte used in the cell as well as the operating conditions of the unit. Fuel cells can also be characterized as either low or high temperature and by the types of fuel or oxidants used. Materials of construction play an important role in determining the limitations of fuel cell systems. In particular, choosing the optimum materials for electrode construction and the appropriate metal catalysts to promote the electrode reactions impacts the long-term performance and cost of a fuel cell system. In this section, the design, construction, and operation of several fuel cell systems will be described highlighting the effects and impact impurities have on overall system performance. For historical purposes, a discussion of AFCs is presented despite the fact that these systems have been developed primarily for space applications and are not likely to be used for stationary power production. In addition, the following fuel cell systems will be described as they have potential applications for terrestrial transportation and stationary power production: PEFC; PAFC; MCFC; and SOFC.

2.1   AFCs

The first commercial fuel cell systems were the AFCs that became available in the 1950s. The most successful application of these fuel cells was in the U.S. space program. AFCs were used to power the Apollo spacecrafts and are currently used in the Space Shuttles. The electrolyte in AFCs is a concentrated KOH solution. For low temperature applications (60-90°C) the KOH concentration is 35-50 wt%. To achieve optimum performance of AFCs with KOH concentrations of 85 wt% the operating temperature was increased to 260°C. These high temperature cells are also operated at high pressures (4-6 atm) to prevent the electrolyte solution from boiling.

Pure H_2 and O_2 are input as the fuel and oxidizer in an AFC. The gas diffusion electrodes are constructed of porous carbon and are doped with Pt to catalyze the oxidation and reduction reactions. The anodes contain 20% Pd in addition to the Pt and the cathodes contain 10% Au and 90% Pt. For higher temperature operations, Ni catalysts are also used. Ni is used for the interconnectors in an AFC stack.

The mobile ions in the system are the OH^- ions in the alkaline solution that are transported from the cathode, where reduction of O_2 occurs, to the anode, where oxidation of H_2 occurs. Water is produced at the anode. The following reactions define the operation of AFCs:

Anode: $H_2 + 2OH^- \equiv 2H_2O + 2e^-$
Cathode: $\frac{1}{2}O_2 + H_2O + 2e^- \equiv 2OH^-$
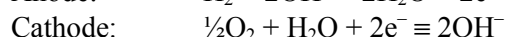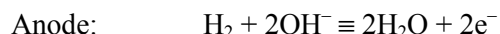
Although AFCs have the highest electrical efficiency of all fuel cell systems (60% LHV), they are extremely sensitive to impurities. The presence of N_2 and impurities in the gas streams substantially reduce the cell efficiency. The presence of even small amounts of CO_2 is detrimental to the long-term performance of AFCs because K_2CO_3 forms and inhibits gas diffusion through the carbon electrodes. The small amounts of CO_2 in air (~300 ppm) precludes the use of air as the oxidant in an AFC. This restriction limits the use of these fuel cell systems to applications such as space and military programs, where the high cost of providing pure H_2 and O_2 is permissible. Because pure gases are used, AFCs can generate pure, potable water for consumption during space missions.

2.2   PEFCs

PEFCs contain a proton conducting ion exchange membrane as the electrolyte material. Consequently, these fuel cell systems are also called Proton Exchange Membrane Fuel Cells (PEMFC) or Ion Exchange Membrane Fuel Cells (IEMFC). The membrane material is a fluorinated sulfonic acid polymer commonly referred to by the trade name given to a material developed and marketed by DuPont - Nafion®. The acid molecules are immobile in the polymer matrix; however, the protons associated with these acid groups are free to migrate through the membrane from the anode to the cathode, where water is produced. The electrodes in a PEFC are made of porous carbon cloths doped with a mixture of Pt and Nafion®.

PEFCs use H_2 as the fuel and O_2 as the oxidant. The PEFC is insensitive to CO_2 so air can be used instead of pure O_2 and reforming hydrocarbon fuels can produce the H_2. Thermally integrating fuel reformers with operating temperatures of 700-800°C with PEFCs that operate at 80°C is a considerable challenge. The PEFC is defined by the following reactions:

Anode: $H_2 \equiv 2H^+ + 2e^-$
Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \equiv H_2O$
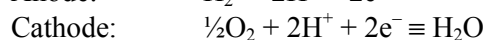
PEFCs have received considerable attention lately as the primary power source in electric vehicles for several reasons. Since the electrolyte is a polymeric material, there is no free corrosive liquid inside the

cell (water is the only liquid), hence material corrosion is kept to a minimum. PEFCs are also simple to fabricate and have a demonstrated long life. On the other hand, the polymer electrolyte (Nafion®) is quite expensive and Pt loadings in the electrodes are quite high so the fuel cell cost is high. The power and efficiency of a PEFC is also very dependent on the water content of the polymer electrolyte, so water-management in the membrane is critical for efficient operation. The conductivity of the membrane is a function of the number of water molecules available per acid site and if the membrane dries out, fuel cell power and efficiency decrease. If water is not removed from the PEFC the cathode can become "flooded" which also degrades cell performance.

The required moisture content of the membrane is what limits the operating temperature of a PEFC to less than 120°C. This temperature ensures that the by-product water does not evaporate faster than it is produced. Low operating temperatures equates to high Pt loadings in the electrodes to efficiently catalyze the oxidation and reduction reactions. The Pt content of the electrodes also necessitates that the CO content of the fuel gas be very low (< 5 ppm) because CO blocks the active sites in the Pt catalyst. Therefore, if a hydrocarbon reformer is used to produce H_2, the CO content of the fuel gas needs to be greatly reduced. This is usually accomplished by oxidation of CO to CO_2, using a water gas shift reactor, or using pressure swing adsorption to purify the hydrogen.

2.3   PAFCs

Other than the AFCs described above, PAFCs are closer to commercialization than other fuel cell systems [Appleby (1996)]. The two intended commercial uses for PAFCs are 1) distributed power using reformed natural gas as a fuel; and 2) for small-scale, on-site cogeneration. Air is used as the oxidant. In contrast to the AFC, PAFCs are tolerant of CO_2 because concentrated phosphoric acid (H_3PO_4) is used as the electrolyte. Compared to other inorganic acids, phosphoric acid has relatively low volatility at operating temperatures of 150-220°C. Protons migrate from the anode to the cathode through 100% H_3PO_4 that is immobilized in a SiC-poly(tetrafluoroethylene) matrix. Electrodes are made of platinized, gas permeable graphite paper. The water produced at the cathode is removed with the excess O_2 and the N_2. PAFCs have demonstrated excellent thermal, chemical, and electrochemical stability compared to other fuel cell systems. PAFCs are defined by the following reactions:

Anode: $H_2 \equiv 2H^+ + 2e^-$
Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \equiv H_2O$
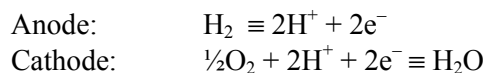
To optimize the ionic conductivity of the electrolyte, operating temperatures are maintained between 150-220°C at pressures ranging from atmospheric to ~8 atm. Reduction of oxygen is slower in an acid electrolyte than in an alkaline electrolyte, hence the need for Pt metal in the electrodes to help catalyze the reduction reactions. CO poisoning of the Pt electrodes is slower at PAFC operating temperatures than at lower temperatures so up to 1% CO in the fuel gas produced during the reforming process can be tolerated. At lower temperatures CO poisoning of the Pt in the anode is more severe.

Aside from the CO produced during hydrocarbon reforming, the concentration of other impurities must be low compared to the reactants and diluents. Sulfur gases (mainly H_2S and COS) that originate from the fuel gas can poison the anode by blocking active sites for H_2 oxidation on the Pt surface. Molecular nitrogen acts as a diluent but nitrogen compounds like NH_3, HCN, and NO_x are potentially harmful impurities. NH_3 acts as a fuel, however, the oxidant nitrogen compounds can react with the H_3PO_4 to form a phosphate salt, $(NH_4)H_2PO_4$. Unacceptable performance losses can occur if the concentration of this phosphate salt in the electrolyte increases above 0.2 mole%.

2.4   MCFCs

MCFCs contain an electrolyte that is a combination of alkali (Li, Na, and K) carbonates stabilized in a $LiAlO_2$ ceramic matrix. The electrolyte should be pure and relatively free of alkaline earth metals. Contamination by more than 5-10 mole % of $CaCO_3$, $SrCO_3$, and $BaCO_3$ can lead to performance loss. Electrons are conducted from the anode through an external circuit to the cathode and negative charge is conducted from the cathode through the electrolyte by CO_3^{2-} ions to the anode. Water is produced at the anode and removed with the CO_2. The CO_2 needs to be recycled back to the fuel cell to maintain the electrolyte composition. This adds complexity to the MCFC systems. The oxidation and reduction reactions that define MCFC operation are as follows:

Anode: $H_2 + CO_3^{2-} \equiv H_2O + CO_2 + 2e^-$
                        $CO + CO_3^{2-} \equiv CO_2 + 2e^-$
Shift: $CO + H_2O \equiv H_2 + CO_2$
Cathode: $\frac{1}{2}O_2 + CO_2 + 2e^- \equiv CO_3^{2-}$
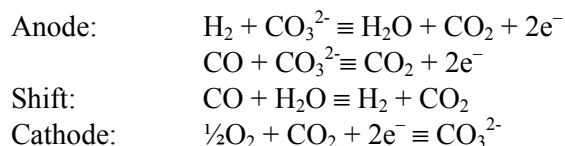
MCFCs typically operate at temperatures between 600-700°C providing the opportunity for high overall system operating efficiencies, especially if the waste heat from the process can be utilized in the fuel reforming step or for cogeneration. Operating temperatures higher than 700°C lead to diminishing gains in fuel cell performance because of electrolyte loss from evaporation and increased high temperature materials corrosion. The high operating temperature of a MCFC system also provides for greater fuel flexibility; a variety of hydrocarbon fuels (natural gas, alcohols, landfill gas, syngas from petroleum coke, coal and biomass, etc.) can be reformed to generate hydrogen for the fuel cell. The CO from biomass and coal gasification product gas and reformed hydrocarbons is not used directly as a fuel but when mixed with water vapor can produce additional hydrogen via the water-gas shift reaction. Oxygen or air is used as the oxidant. An attractive design incorporates an internal fuel reformer within the fuel cell eliminating the need for a separate fuel processor.

A higher operating temperature also means that less expensive materials can be used for the electrocatalysts in the electrodes; Pt is not required and Ni is used as the catalyst. The Ni in the cathode becomes oxidized and lithiated (from contact with the electrolyte) during initial operation of a MCFC so that the active material is Li-doped NiO. Unfortunately, NiO is soluble in molten carbonates leading to the possible dissolution of the cathode and dispersion of metallic nickel in the electrolyte, which can eventually short-circuit the electrodes. This is one of the materials issues that is being investigated to improve the long-term operability of MCFC systems.

The anode contains Ni doped with 10% Cr to promote sintering. An external methane reformer is not needed in a MCFC system because the presence of Ni in the anode at MCFC operating temperatures is very effective for internal CH_4 reforming at the anode. Internal methane reforming can increase overall system efficiencies, but can also induce unwanted temperature gradients inside the fuel cell that may cause materials problems. Catalyst poisoning is also an issue if the sulfur content of the reagent gases is greater than 10 ppm, similar to all Ni-based fuel-reforming systems. Coke formation on the anode from fuel reforming can also be an issue.

2.5   SOFCs

SOFC systems operate between 900-1000°C, higher than any other fuel cell system. At these operating temperatures, fuel composition is not an issue because in the presence of enough water vapor and oxygen complete oxidation will be achieved, even in the absence of catalytic materials. High overall system efficiencies are possible with waste heat recovery. The electrolyte material in a SOFC is yttrium (8-10 mol%) stabilized zirconia (YSZ). This material is a solid with a stable cubic structure and very high oxide

conductivity at SOFC operating temperatures. The mobile O^{2-} ions migrate from the cathode to the anode where water is produced. The electrochemical reactions occurring in a SOFC system are as follows:

Anode: $\quad\quad\quad H_2 \equiv 2H^+ + 2e^-$
Cathode: $\quad\quad ½O_2 + 2H^+ + 2e^- \equiv H_2O$
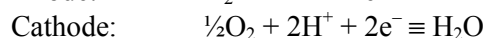
Similar to the MCFC systems, the high operating temperatures of the SOFCs provides fuel flexibility without the need for expensive catalysts in the electrodes. The cathode in a SOFC consists of mixed oxides with a perskovite crystalline structure, typically Sr-doped lanthanum manganate ($LaMnO_3$). The anode material is a Ni cermet (ceramic and metal composite). It contains metallic Ni for catalytic activity in a YSZ support. The YSZ adds mechanical, thermal, and chemical stability – chemical and thermal compatibility between the anode and the electrolyte is not an issue. Like the MCFC systems, internal methane steam reforming at the Ni-based anode in the presence of water vapor is possible in SOFC systems.

Overall, SOFC systems can tolerate impurities because of their high operating temperatures. Sulfur tolerances can be up to two orders of magnitude higher in SOFCs than in other fuel cell systems because of the high operating temperatures. Energy efficient, high temperature sulfur removal methods are used to lower the sulfur content of the gas to less than 10 ppm. At the same time, the high operating temperatures of SOFCs can cause considerable materials issues like material incompatibilities (thermal and chemical) and corrosion.

Significant research and development efforts have gone into technically and cost-effectively addressing materials issues in SOFC systems for commercial applications. This is reflected in the variety of designs for SOFC systems. There are three general types of designs for SOFC systems: tubular, bipolar monolithic, and bipolar planar. The bipolar designs have a bipolar plate that prevents reactant gases in adjacent cells from mixing and provides serial electrical interconnectivity between cells. The single cells are stacked with interconnectors, gas channels, and sealing elements in between. There are two types of tubular designs: seal-less and segmented cell in-series. A single cell in a tubular SOFC consists of a long porous YSZ ceramic tube that acts as a substrate. The cathode, followed by the electrolyte, and finally the anode are deposited on the outer surface of the tube. A portion of the tube is left with a strip of the cathode covered by the interconnector material to make the electrical connection. Individual tubes are arranged in a case and air flows inside the tubes while fuel flows around the outside of the tubes.

Developments in SOFC systems that operate at intermediate temperatures (550-800°C) are currently receiving considerable attention. Reducing the operating temperature of SOFC systems is being pursued in an attempt to reduce the cost of these systems. Some of the benefits of a reduced operating temperature include: better thermal integration with fuel reformers and sulfur removal systems, reduced material issues such as less thermal stress and more material flexibility, lower heat loss, shorter time to achieve operating temperature, and less corrosion. Capitalizing on the benefits of lower SOFC operating temperatures is an area of continued and future research and development.

2.6   Fuel Cell Tolerances

In the descriptions of the individual fuel cell systems many of the major impurities were identified, however, they will be repeated in this section with additional discussion about more of the minor impurities that may have been overlooked. This section will summarize all of the gas impurities and the tolerances the individual fuel cell systems have towards these impurities. Fuel cell systems will be discussed in the same order as above. The impurity tolerances for the fuel cell systems are summarized in Table 1.

2.6.1 AFC

The least fuel flexible fuel cell system is the AFC. Carbon dioxide is a major contaminant in AFC systems because the KOH electrolyte slowly converts to K_2CO_3 and degrades long term performance. Therefore, only pure H_2 and O_2 can be used in these systems. Even the trace level of CO_2 in air precludes its use in AFC's as the oxidant.

2.6.2 PEFC

PEFCs are tolerant to CO_2, so air can be used as the oxidant and hydrocarbon reformers can potentially be used to generate the H_2 for the reductant. The low temperature operation of the PEFC systems means high Pt loadings on the electrodes are required for efficient operation and CO produced during reforming acts as a catalyst poison. In PEFC systems, the CO content of the input gas stream should be reduced to less than 10 ppm [Ledjeff, Roes, and Wolters, (2000)]. Assuming CO levels are acceptable for PEFC operation, sulfur gases (mainly H_2S) can also poison the Pt catalyst in the electrodes. This sulfur can be present as the odorant in natural gas or be formed during solid fuel (petroleum coke, coal or biomass) gasification. Sulfur also deactivates the Ni-based fuel reforming catalysts.

2.6.3 PAFC

PAFC CO and H_2S tolerances are similar to the PEFC systems. Additional impurities in the fuel gas are also an issue with PAFC systems. The H_2S level should be below 4 ppm because it is a poison to both the catalysts in the fuel cell electrodes and in the fuel reformer [Speigel, et al. (1999)]. Halogens should be kept to similar levels to avoid corrosion in the fuel processing system [Speigel, et al. (1999)]. Ammonia in the fuel gas should be kept below 0.5% to minimize NO formation and to maintain fuel cell performance [Speigel, et al. (1999)]. Excessive ammonia in the fuel gas will lead to the accumulation of ammonium phosphate salts in the electrolyte and increase the probability of short circuiting and poor conductivity [Fuel Cell Handbook (2000)]. Excessive tar levels (> 0.5%) in the fuel gas can plug fuel gas transfer lines and may cause carbon build up (coking) in the fuel reformer.

2.6.4 MCFC

MCFC systems operate at relatively high temperatures and are therefore much more fuel flexible. MCFC systems can tolerate CO and CO_2 in addition to hydrocarbons. CO_2 is actually a necessary component in maintaining the carbonate content in the electrolyte and is recirculated back into the fuel cell. Halide levels in the input gas stream should be reduced to 10-0.1 ppm because formation of volatile alkali halides in the electrolyte cause more rapid vaporization and accelerated electrolyte loss that decreases the long term performance of the fuel cell [ERC (1998); Fuel Cell Handbook (2000)]. The introduction of alkaline earth metals into the electrolyte also leads to reduced cell performance. Levels of $CaCO_3$, $SrCO_3$, and $BaCO_3$ in the electrolyte should be maintained below 5-10 mole% [Kordesch and Simader, (1996)].

Internal reforming of CH_4 and other hydrocarbons at the anode can be achieved at MCFC operating temperatures. Consequently, MCFC systems are very tolerant of hydrocarbons in the fuel gas. According to Bossart, et al (1990), the input fuel gas to a MCFC system can contain 12 vol% saturated hydrocarbons (methane included), 0.2 vol% olefins, 0.5 vol% aromatics, and 0.5 vol% cyclics. Excessive levels of higher molecular weight hydrocarbons can cause typical problems like plugging and fouling of pipes, fuel transfer lines, heat exchangers, and particle filters. These tars can also deactivate sulfur sorbents and lead to coke formation on the anode.

Sulfur, in the form of H_2S, must be removed from the fuel gas stream below 1 ppm to avoid poisoning the Ni catalyst in the anode [Fuel Cell Handbook (2000); ERC (1998)]. H_2S will deactivate the Ni catalysts decreasing the fuel reforming efficiency.

2.6.5 SOFC

SOFC systems operate at higher temperatures than MCFC systems and offer similar fuel flexibility and tolerances to impurities. SOFC systems are tolerant of CO, CO_2, and hydrocarbons. CO can be a fuel in a SOFC or with water vapor it can be shifted to form H_2, that is consumed, and CO_2. Hydrocarbon fuels are usually reformed in an external reforming unit and coking of the Ni-based catalysts is always a concern. SOFC systems require very stringent acid gas removal because they can only tolerate 1 ppm H_2S and 1 ppm halides in the fuel gases [Fuel Cell Handbook (2000)]. Ammonia can be tolerated up to 0.5 vol% [Fuel Cell Handbook (2000)].

Table 1: A Summary of Fuel Cell Tolerances

	PEFC	PAFC	MCFC	SOFC
Operating Temp ^oC	70-90	160-210	600-700	800-1000
H_2	Fuel	Fuel	Fuel	Fuel
CO_2	Diluent	Diluent	Re-circulated	Diluent
CO	Poison – 10 ppmv[a,b]	Poison – 10 ppmv[b]; 1% at anode[c]	With water –shifted to make H_2	With water – shifted to make H_2
CH_4	Inert, Fuel w/ reformer	Inert, Fuel w/ reformer	Fuel – reformed internally or externally	Fuel – reformed
C_2 - C_6		Poison - <0.5% olefins	Plugging & coking Fuel w/reformer Sat HC – 12% vol[e] (CH_4 included) Olefins - 0.2 vol%[e] Aromatics – 0.5 vol[e]% Cyclics – 0.5 vol%[e]	Fuel – similar to MCFC in regards to high molecular weight HC's
Particulates			10 ppmw[e]; <0.1g/l of particles > 3μm[c]	
Trace Species:	ppm, dry basis			
Sulfur		Poison < 20ppm H_2S[c] < 50 ppm H_2S + COS[c]	Poison < 10 ppm H_2S in fuel < 1 ppm SO_2 in oxidant <0.5 ppm H_2S[c] <0.1 ppm H_2S[f]	Poison <1 ppm H_2S[c]
NH_3		Poison < 0.2 mole% ammonium phosphate in electrolyte[c]	Fuel?/Inert - < 1vol%[c]	Fuel < 5000 ppm[c]
Halogens (HCl)		Poison 4ppm[d]	Poison < 1 ppm[c] <0.1 ppm[f]	Poison - <1ppm[c]
Alkali metals			Electrolyte loss 1-10 ppm[g]	
Other	Water maintenance		Electrolyte balance w/ CO_2 recirculation	SiO_2 deposition

[a]Ledjeff, Roes, and Wolters (2000)
[b]Kordesch and Simader (1996)
[c]Fuel Cell Handbook 5th Edition (2000)
[d]Speigel, et al. (1999)
[e]Bossart, et al. (1990)
[f]ERC (1998)
[g]Lobachyov and Richter (1998)

3   FUEL GAS OPTIONS

Fuel cell systems can utilize a variety of fuels for conversion to electricity; however, the common reductant in all systems is H_2. Unless the H_2 is supplied directly to the fuel cell system, hydrogen needs to be generated by reforming other fuels and processed to meet the requirements of a given fuel cell system. This section describes the potential use of various hydrocarbon-rich gases for distributed or centralized electricity production via fuel cell systems. Omitted is a discussion of the use of liquid fuels such as methanol, gasoline, and other distillates that have been targeted for fuel cell transportation applications.

3.1   Natural Gas

Natural gas delivered in a pipeline typically consists of methane (75-92%), ethane (1-6%), propane (1-4%), higher hydrocarbons (less than 2.5%), CO_2 (less than 1%), and N_2 (perhaps 5-15%). Sulfur containing gases (mercaptans, disulfides, or thiophanes) are added in small quantities as odorants for leak detection. The total sulfur content of pipeline natural gas is on the order of 10-80 ppm with about 4 ppm H_2S and 4 ppm mercaptans. [Bartok and Sarofim, (1991)]

3.2   Landfill Gas

Landfills remain the most common means of disposal for municipal and industrial wastes. Physical, chemical, and biological decomposition of waste materials results in the production of a medium energy content gas that contains primarily methane and carbon dioxide. Collecting landfill gas is a mature technology and may receive more attention in the future if landfill gas emissions are regulated. The typical composition of landfill gas is: 40-45% CH_4, 35-50% CO_2, 1-10% $H_2O(g)$, 0-20% N_2, 250-3000 ppm hydrocarbons, up to 200 ppm H_2S, and a range of chlorine containing compounds [ERC, (1998)]. The composition of landfill gases collected at individual sites can be found in the literature [Speigel, et al. (1999b); He, et al. (1997)] and, while the bulk gas compositions are similar the levels of the traces compounds can vary significantly. Landfill gas is also saturated with water vapor.

3.3   Anaerobic Digestion Product Gas

Anaerobic digestion is the natural biological process of microbial consumption of organic matter in the absence of oxygen to produce methane, water, and carbon dioxide. Wastewater treatment facilities in the United States use anaerobic digestion to reduce the solids content of sewage sludge. Anaerobic digestion is also being considered to treat animal wastes to eliminate environmentally unattractive alternatives like swine lagoons. The major components of anaerobic digester gas, on a dry basis, are: CH_4 (55-65%), CO_2 (30-40%), N_2 (1-10%), and less than 0.5% O_2. Trace anaerobic digester gases include up to 200 ppm H_2S, 4 ppm halogens, and other hydrocarbons [Spiegel and Preston (2000); Spiegel, et al. (1999a)]. Anaerobic digester gas is usually saturated with water vapor.

3.4   Gasification Synthesis Gas

Gasification of solids fuels, coal, biomass, MSW, etc., in a reducing atmosphere is yet another approach used to generate a hydrogen-rich product gas. There are several different types of gasification technologies being developed and the type of gasifier and the associated operating conditions directly affect the composition of the product gas. Gasifiers operate with air or oxygen to achieve partial oxidation of the solid fuel and can have moving bed, fluidized bed, or entrained flow designs that operate at atmospheric or elevated pressures. Air-blown coal gasifiers produce a low energy content gas composed of 10-15% CO_2, 15-30% CO, 10-30% H_2, and 0-5% CH_4 in a balance of N_2 [Bartok and Sarofim (1991)]. Oxygen-blown coal gasifiers produce a slightly higher energy content product gas with 5-35% CO_2, 10-55% CO, 30-40% H_2, and 1-15% CH_4, with only 1-2% N_2 [Bartok and Sarofim (1991)].

Biomass gasifiers generally operate at lower temperatures than coal gasifiers because biomass has a higher oxygen content than coal and is therefore more reactive. Biomass gasifiers can also use steam, air, or pure oxygen to affect the partial oxidation of the fuel. Biomass gasification product gases also have a wide range of compositions depending on the feedstock composition and gasifier operating conditions. In general, biomass gasification synthesis gas contains 10-20% CO_2, 10-45% CO, 1-20% CH_4, 10-30% H_2, and 1-10 % higher molecular weight hydrocarbons, on a dry basis. For air-blown systems 40-50% of the product gas will be N_2 [Craig and Mann, 1996]. A summary of the product gas compositions from several coal and biomass gasification systems is presented in Table 2.

The concentration of the major product gases from gasification systems is relatively similar regardless of the solid feedstock used or the operating temperatures of the reactors. Gasifiers typically produce various contaminants that may cause problems in end use devices. The concentrations of the trace components are very sensitive to fuel composition and operating parameters. Coal typically has a higher sulfur content than biomass and, as a result, the product gas can contain 0.1 to 1% or more H_2S. Depending on the type of gasifier some of the sulfur in the product gases may be oxidized in the form of COS or SO_2. Even though biomass generally has a low sulfur content, H_2S in the product gas can be an issue. The nitrogen content of the coal or biomass will also dictate the amount of ammonia and HCN present in the product gases. Many coals and biomass feedstocks can contain high levels of chlorine that result in a substantial HCl concentration in the product gases. The other major impurities present in gasification product gases are particulates and tars, or condensable organics. Particulates can be carried over bed material or ash from the solid fuel.

Table 2: Gas Compositions from Various Gasification Systems

Gasifier	LURGI Fixed Bed	Destec	Texaco	Low Pressure, Indirect	High Pressure
Fuel	*Illinois 6 coal*	*Wyodek coal*	*Illinois 6 coal*	*Wood*	*Wood*
Operating Temperature °C	750 – O_2 blown	1038 – O_2 blown	1600	826 – steam	830 – Air blown
Reference	A	B	A	C	C
Mole % H_2O	61.8	26.6	16.5		39.91
Products mole%, dry basis					
N_2	0.26	0.82	0.84		40.24
H_2	42.0	37.7	36.3	21.28	14.83
CO_2	30.8	22.5	12.9	13.45	22.38
CO	15.1	37.3	47.7	43.16	11.16
CH_4	8.6	0.13	0.12	15.83	10.83
C_2H_4	0.26			4.62	0.017
C_2H_6	0.52			0.46	0.12
H_2S	1.3	0.19	1.2	0.08	0.008
COS	Trace	0.008			
NH_3	0.8	0.3		0.37	0.10
Tars	0.24			0.40	0.27
Particulates (g/l)	0.016				
Halogens ppm	200				

A – Fuel Cell Handbook (2000); B – Spath, et al. (1999); C – Craig and Mann (1996)

4 INTEGRATING GAS PRODUCERS WITH FUEL CELLS

This section discusses integration issues and focuses on the gas conditioning required distributed and centralized fuel cell power production. In fuel cell power plants, the actual fuel cell itself accounts for only one-third of the size and cost. Ancillary equipment such as fuel processing systems, power conditioners, components for air supply, thermal management systems, water recovery and treatment units, and system control and diagnostics make up the balance of plant. If pure H_2 can be delivered to the fuel cell, much of the fuel processing equipment is not needed, however, high operating costs and issues with hydrogen storage prohibit this option. The existing hydrocarbon infrastructure makes reforming hydrocarbon fuels the cost effective, near-term option for fuel cell power plants.

4.1 Fuel Reforming

The components of a fuel processing system are quite obviously dependent on the type of fuel being used and the type of fuel cell applied. A reforming reactor is necessary to generate hydrogen from hydrocarbon fuels in low temperature fuel cell systems. Fuel reformers operate at high a temperature (700-950°C) that results in poor thermal integration with PEFC and PAFC systems. PEFC and PAFC systems also have low tolerances to the CO that is produced in substantial quantities from natural gas and other hydrocarbon reformers. A separate water-gas shift system is required to reduce CO levels to less than 1% in PAFC systems. PEFC systems will require an additional CO catalytic oxidizer or a methanation reactor to reduce levels to less than 50 ppm. Given these requirements, PEFC systems integrated with fuel reformers do not appear to be the most viable fuel cell system choice. MCFC and SOFC systems have higher operating temperatures than PEFC and PAFC systems resulting in better thermal integration between the fuel cell system and a reforming reactor. In these high temperature systems, internal reforming is an option that would eliminate the need for an external fuel reformer.

4.2 Acid Gas Removal

Acid gas removal systems will be required in all hydrocarbon reforming fuel cell systems because both fuel cells and steam reforming catalysts do not tolerate sulfur. Sulfur removal is necessary even in natural gas fuel cell plants to remove the H_2S, mercaptans, disulfides, and odorants that can be present in various concentrations. Landfill and anaerobic digester gases contain trace amounts of sulfur and the sulfur content of coal or biomass gasification product gas will depend on the sulfur content of the feedstock. Biomass tends to have a much lower sulfur content than coal, however, sub-bituminous western coals have fairly low sulfur contents (~0.5%). There are high and low temperature options for sulfur removal. The hydrodesulfurization concept converts the sulfur species in the fuel to H_2S and uses regenerable metal oxide sorbents to trap the sulfur. ZnO is the most common sulfur sorbent used, however, other materials like FeO and CuO are also used. ZnO guard beds effectively remove sulfur to a few ppm H_2S but 600°C is the upper operating temperature limit. Another low temperature sulfur removal scheme operates at ambient temperature and pressure and converts H_2S via the Claus reaction to elemental sulfur that is adsorbed by a fixed carbon bed [Spiegel, et al. (1999)].

Anaerobic digester and landfill gases have similar compositions and several demonstrations of PAFC systems with these fuel gases have been published [Spiegel, et al. (1999a,b); Spiegel, et al (1997); Staniforth and Kendal, (2000); He, et al. (1997); ERC (1998)]. Halogens in these fuel sources are an additional impurity that needs to be removed. This is easily accomplished with a guard bed containing K_2CO_3 or KOH. The steam reformer in the PAFC systems presumably consumes the non-methane organic hydrocarbons present in the fuel gas; however, carbon deposition (coking) can become a problem. Anaerobic digester gas is usually saturated, so some means of dehumidification will be needed. Particulate removal will also be needed. An advantage of using a PAFC system with landfill and anaerobic digester gases is that the gas is cool and low temperature gas conditioning units can be used

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prior to the fuel reformer. SOFC's [Staniforth and Kendall (2000)] and MCFC's [ERC, 1998] have also been tested with landfill gas.

4.3   Gasification Product Gases

By far the most challenging fuel to utilize in fuel cell systems is gasification product gas. Future integrated gasification fuel cell systems are likely to include MCFC's or SOFC's because of their relatively high tolerance to impurities, internal steam reforming potential, and favorable thermal integration. To date, fuel cells have not been demonstrated on coal or biomass gasification product gases. Several technoeconomic analyses of integrated biomass gasification fuel cell systems have been published [Amos (1998); Lobachyov and Richter (1998); McIlveen-Wright, Williams, and McMullan (2000)]. A demonstration of an integrated coal gasification MCFC system is scheduled for 2003 [Steinfeld, et al. (2000)]. PAFC and PEFC systems could be integrated with gasification systems, however, the fuel processing would be significantly more complex and greater penalties in loss of efficiency will be incurred.

The contaminant levels in a coal or biomass gasification product gas stream are highly dependent upon the input feedstock composition and the gasifier operating conditions. The halogen content of the gasification product gas can be substantial depending on the Cl content of the coal or biomass feedstock used. Coal can contain relatively high levels of S (up to 5%). This translates into high H_2S concentrations in the gasifier product gas and will require several steps of sulfur cleanup to reduce incident H_2S levels to < 10 ppm in MCFC systems and below 1 ppm in SOFC systems. Sulfur scrubbing would be accomplished by a COS hydrolysis reactor, bulk H_2S removal, sulfur recovery (Claus process), and sulfur polishing with ZnO beds.

4.3.1   Tars

Gasification processes also produce varying levels of organic tars and particulate matter. Tars can cause coke to form on the fuel reforming catalyst or on the fuel cell electrodes. Tars can also deactivate and foul sulfur removal systems. Tars can be removed from the gas stream in the fuel reformer or by separate hot gas tar removal catalysts. It is also possible to mitigate tars in the gasification vessel by adding tar destruction catalysts such as sintered dolomite directly to the fixed, fluidized, or entrained bed.

4.3.2   Particulate Matter

Particulate matter can be removed from the hot product gases with cyclones or barrier (bag) filters. The particulate matter can be bed material that has been carried out of the gasifier or ash from the solid fuel. Coal ash is comprised of mineral matter and is usually high in Fe, Ca and Al. These inorganic materials can deactivate reforming or sulfur removal catalysts and can impact the long-term performance of a MCFC or SOFC by poisoning the electrolyte. Biomass ash typically contains less Fe and Al than coal but has a higher Si, K, Na, and sometime Cl content than coal ash. Silica is detrimental to the electrolyte in a SOFC and the Cl and additional K can upset the electrolyte balance in a MCFC.

Efficient particulate removal may capture most of the alkali metals found in biomass and coal ashes. Alkali metals in biomass, however, tend to be more volatile than in coal because a large fraction of alkali metals in coal are found in refractory mineral matter that is not present in biomass ashes. Therefore, alkali metal vapors may form during biomass gasification and have deleterious effects on steam reforming catalysts, fuel cell electrodes, and electrolytes. A low temperature quench may be sufficient if high concentrations of alkali vapors are present in the product gases. Alkali fume is also known to form at gasification temperatures from biomass materials and removal of these sub-micron size particles may require hot gas filtration.

5   CONCLUSIONS

High costs associated with materials of construction and balance of plant currently hinder attempts to commercialize fuel cell systems for distributed and centralized power production. Significant research and development is being conducted to lower these barriers to commercialization and reduce the capital costs of fuel cell systems while improving system performance and reliability. Ancillary components in a fuel cell power plant account for nearly half of the system yet account for nearly all of the unscheduled outages in hydrocarbon-fuelled fuel cell systems. A major ancillary component that requires considerable attention is the fuel processing system.

Acid gas removal systems will be required in all hydrocarbon reforming fuel cell systems because both fuel cells and steam reforming catalysts do not tolerate sulfur. They will be necessary even for systems using natural gas, the simplest hydrocarbon fuel. Halogen guard beds will likely be required for all fuel cell power systems as well to minimize long term, high temperature corrosion.

The MCFC and SOFC high temperature systems offer the best thermal integration opportunities with coal and biomass gasification systems. The technical challenge will be to design a fuel processing system to pre-condition the product gases before they enter the fuel cell stack. These systems will also require particulate removal to remove carried over bed material and ash. Removal of biomass and coal ash is also needed to control alkali metal contamination. Hot gas filtration or quenching is an option for removal of high temperature alkali metal vapors released from biomass and coal ashes. Tar removal will also be necessary to avoid plugged fuel lines, fouled catalytic sulfur removal systems, and coke formed on the fuel cell electrodes and steam reforming catalysts.

The main challenge involves the fact that coal and biomass feedstocks have incredibly variable compositions. This would suggest that fuel processing systems, while generic in one sense, will have to be customized for many individual situations. This will require integrating the fuel procesor sub-systems and poses significant engineering and technical challenges for designing and integrating gasification systems, fuel processing systems, and fuel cell stacks.

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7   FUEL CELL DEVELOPERS/MANUFACTURERS

A comprehensive listing of fuel cell developers can be found on the World Wide Web at http://216.51.18.233/fcdevel.html under the Fuel Cell 2000 homepage. Another useful on-line source of information about fuel cells can be found on the National Fuel Cell Research Center homepage at http://www.nfcrc.uci.edu.

Analytic Power Corporation / Dais-Analytic Corporation
11552 Prosperous Drive
Odessa, FL 33556
Phone: (727) 375-8484 Fax: (727) 375-8485
info@daisanalytic.com
www.analyticpower.com

DAC has oriented its technology, product and business development activities to focus on its proprietary membrane materials and on small fuel cell power plants. Stationary fuel cell applications include 3 kW power plants for homes and small commercial businesses, fueled by natural gas, propane, ammonia or diesel and based on PEM technology.

BCS Technology, Inc.
2812 Finfeather Road
Bryan, TX 77801 USA
Tel:(979) 823-7138
bcstech@txcyber.com
http://www2.cy-net.net/~bcstech/

BCS Technology has been involved on the development of Proton Exchange Membrane (PEM) fuel. BCS Technology offers regular forced-flow type stacks of capacities in excess of 1 kW and convection type fuel cell stacks of capacities up to 150 W.

Ballard Power Systems
9000 Glenlyon Parkway
Burnaby, BC V5J 5J9
Phone: (604) 454-0900 Fax: (604) 412-4700
http://www.ballard.com/default.asp

Ballard Power Systems is developing, manufacturing and marketing zero-emission proton exchange membrane fuel cells for use in transportation, electricity generation and portable power products in the 1-25 kW range.

Ceramatec
2425 South 900 West
Salt Lake City, Utah 84119
Phone: 801-972-2455 Fax: 801-972-1925

Have developed a 1.4 kW solid oxide fuel unit has been demonstrated with natural gas.

Ceramic Fuel Cells Limited
170 Browns Road
Noble Park Victoria, 3174 Australia

Tel: +61 3 9554 2300 Fax: +61 3 9790 5600
enquiries@cfcl.com.au
http://www.cfcl.com.au/
Ceramic Fuel Cells Limited (CFCL) is a sole-purpose corporation totally focused on the development of Solid Oxide Fuel Cell (SOFC) Technology in the 25-200 kW range.

ElectroChem, Inc.
400 W. Cummings Park
Woburn, MA 01801 USA
phone: (781) 938-5300
fax: (781) 935-6966
fuelcell@fuelcell.com

Products include PEM fuel cells and stacks, as well as Phosphoric Acid Fuel Cells. ElectroChem has also sold its "fuel cell in a suit-case" to government agencies and private industries both in the US and abroad. ElectroChem's has also introduced the EC-200 Power Pak, a complete power unit with both AC and DC outlets capable of powering an everyday appliance such as a radio.

FuelCell Energy, Inc. (Corporate Headquarters)
3 Great Pasture Road
Danbury, CT 06813
Phone: (203) 825-6000
http://www.ercc.com/

Offer direct, molten carbonate fuel cell systems in three sizes - 300 kW, 1.5 MW, and 3.0 MW.

Global Thermoelectric, Inc.
4908 52nd St. SE
Calgary, AB T2B 3R2
Phone: (403) 204-6100 Fax: (403) 204-6105
e-mail: globalhq@globalte.com
http://www.globalte.com/

Developing SOFC systems, no products available yet.

H Power Corp.
1373 Broad Street
Clifton, New Jersey 07013
Tel 1-973-450-4400 Fax 973-450-9850
http://www.hpower.com/

H Power designs, manufactures and sells Proton Exchange Membrane (PEM) fuel cell systems for on-site stationary power (1 to 25 kW units) for use in residences, farms, small commercial establishments and industrial facilities, and telecom applications. Portable and mobile power units with outputs up to 15 kilowatts are available to power electronic equipment and personal portable electronic devices.

Hydrovolt Energy Systems Inc.
3410 Industrial Blvd. Suite 105
West Sacramento, CA 95691
Phone (916) 371-7501 Fax (916) 371-7505
http://www.hydrovolt.com/

Hydrovolt's generators are powered by Solid Oxide Fuel Cells that are currently available in the following products:

- Hydro-Gen 3000, 3kW constant / 5 Kw peak output, stationary power generator.
- Hydro-Gen 6000, 6kW constant / 15 Kw peak output, stationary power generator.
- Bio-Gen hydrogen producing bio-gasafier, (for true energy independence). Makes hydrogen gas from coal or wood pellets.
- Hydro-Gen Portapower, 1kW portable gasoline fueled, fuel cell powered generator.

International Fuel Cells
195 Governors Highway
P.O. Box 739
South Windsor, CT 06074
Voice: (860)-727-2200
Fax: (860)-727-2319
http://www.internationalfuelcells.com

International Fuel Cells (IFC), a unit of United Technologies Corp., has developed and commercialized fuel cells for commercial, transportation, residential and space applications. IFC has more than 40 years of experience in the fuel cell business. Since 1966, all of the more than 100 U.S. manned space flights have operated with IFC-supplied fuel cells. IFC fuels cells provide efficient, reliable electrical power -- as well as drinking water for astronauts -- and have logged more than 70,000 hours in space. IFC is also offers commercial stationary fuel cell systems. IFC's PC25™ fuel cell power plant produces 200 kW of electricity and 700,000 BTUs of usable heat. IFC has delivered more than 200 PC25 systems and has installed units in 15 countries on four continents.

McDermott Technology, Inc.
1562 Beeson Street
Alliance, Ohio 44601-2196
(330) 829-7422
http://www.mtiresearch.com/

Developing planar solid-oxide fuel cells (pSOFC) and fuel processors that produce the hydrogen needed for fuel cells to operate. Currently have a 2-kWe technology demonstration unit system.

Nuvera Fuel Cells, Inc.
15 Acorn Park
Cambridge, MA 02140 USA
(617) 498-5398
www.nuvera.com

Nuvera is a designer and developer of fuel processors, fuel cell stacks, and integrated PEM fuel cell systems for stationary and transportation applications. Nuvera was formed in April 2000 through the merger of DeNora Fuel Cells S.p.A and Epyx Corporation, the fuel cell division of Arthur D. Little, Inc.

Plug Power
968 Albany-Shaker Road
Latham, NY 12110 USA
Phone: (518) 782-7700 Fax: (518) 782-7914
http://www.plugpower.com/

Plug Power's is developing 7 kW PEM fuel cells that run on natural gas or propane designed to meet the energy needs of a typical household.

Proton Energy Systems, Inc.
50 Inwood Road
Rocky Hill, CT 06067 USA
Phone: (860) 571-6533, fax (860) 571-6505
http://www.protonenergy.com

Proton has developed 100 kW reversible PEM fuel cell systems.

Siemens Power Generation
Siemens AG 2000
Power Generation
Freyeslebenstrasse 1, 91058 Erlangen, Germany
http://w4.siemens.de/kwu/e/produkte/komp_u_sys08.htm

Siemens Westinghouse is currently developing a 250 kW and a 1 MW SOFC cogeneration systems, operating at atmospheric pressure with electrical efficiency of 47-50% and overall system energy efficiency of >80%, assuming steam/hot water or other cogeneration. Also being developed are 300 kW and 1 MW hybrid system SOFC/gas turbine systems, operating at elevated pressures of 3-4 atmospheres, with electrical efficiencies of 58-70%, and overall system energy efficiency of ~80% if hot water is also produced.

Sulzer Hexis Ltd
Hegifeldstrasse 30
P.O. Box 65
CH-8404 Winterthur
Switzerland
Tel. +41-52-262 6311 (exchange) Tel. +41-52-262 8276 (direct) Fax. +41-52-262 6333
E-mail: hexis@sulzer.com
http://www.hexis.ch/

Sulzer Hexis specialties are the conception, development and fabrication of planar high-temperature fuel cells (SOFC), particularly in the areas of material development, process control and system integration. Current designs are 1.5 kW SOFC systems.

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13. ABSTRACT *(Maximum 200 words)*

This report is a review of the recent literature exploring the issues of integrating fuel cells with various sources of fuel gas, with particular attention to the fuel-processing step of a fuel cell system. A brief discussion of the available fuel cell technologies is presented highlighting the tolerances of fuel cell systems to impurities in the fuel gases. For a more comprehensive description of fuel cell systems, please consult the Fuel Cell Handbook (5th edition, 2000). This report also outlines a description of several sources of fuels and their compositions followed by a discussion how these fuel sources might be integrated with fuel cell systems for distributed and centralized power production.

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